# Galaxy Zoo: A correlation between coherence of galaxy spin chirality and star formation efficiency\*

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#### ABSTRACT

We report on the finding of a correlation between galaxies' past star formation activity and the degree to which neighbouring galaxies rotation axes are aligned. This is obtained by cross-correlating star formation histories, derived with MOPED, and spatial coherence of spin direction (chirality), as determined by the Galaxy Zoo project, for a sample of SDSS galaxies. Our findings suggest that spiral galaxies which formed the majority of their stars early (z>2) tend to display coherent rotation over scales of  $\sim 10 \mathrm{Mpc}/h$ . The correlation is weaker for galaxies with significant recent star formation. We find evidence for this alignment at more than the  $5\sigma$  level, but no correlation with other galaxy stellar properties. This finding can be explained within the context of hierarchical tidal-torque theory if the SDSS galaxies harboring the majority of the old stellar population where formed in the past, in the same filament and at about the same time. Galaxies with significant recent star formation instead are in the field, thus influenced by the general tidal field that will align them in random directions or had a recent merger which would promote star formation, but deviate the spin direction.

**Key words:** cosmology: theory - galaxies

## 1 INTRODUCTION

In our progress to understand how galaxies have formed and evolved, it has become recently clear (e.g. Jimenez et al. (2008)) that the present stellar mass of galaxies determines most of the galaxy properties. It is thus possible to predict on average what the star formation, metallicity, environment, etc. a galaxy has by simply measuring its current stellar mass. However, second order differences among the prop-

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erties of galaxies with the same stellar mass exist and need to be explained. One of the most obvious physical mechanisms to explain this second parameter is the spin of the dark matter halo. It is now 60 years since Hoyle's seminal paper on the subject (Hoyle 1949) that showed how angular momentum in galaxies can be generated via the tidal field of the other galaxies. Later on, Doroshkevich (1970) developed the tidal torque theory within the framework of hierarchical galaxy formation that determines the amplitude and direction of the spin of a dark matter halo based on the surrounding dark matter field (see Schaefer (2008) for a recent review). Numerical N-body simulations produce results that are in good agreement with the theoretical predictions, although linear theory is not always sufficient to determine the final angular

momentum of a collapsed object (e.g., Barnes & Efstathiou (1987); Porciani et al. (2002) and references therein). In addition mergers are expected to significantly alter a halo final spin (Hetznecker & Burkert 2006).

The amplitude of the dark matter halo spin will influence the radius where baryons will settle into a disk (Fall & Efstathiou 1980; White & Rees 1978), thus influencing its density and therefore the star formation history of the galaxy. The influence of spin on star formation history has been studied in detail Toomre (1964); Dalcanton et al. (1997); Jimenez et al. (1997); Mo et al (1998); Avila-Rese et al. (1998).

One interesting feature of tidal-torque the-(Heavens & Peacock ory in hierarchical models Catelan & Porciani 2001; Catelan et al. 1988: Crittenden et al. 2001; Porciani et al. 2002; Hahn et al. 2007) is the prediction of correlated spin directions and that the spin direction for dark halos is strongly influenced by the halo environment. Pen et al. (2000) reported a detection of galaxy spin correlations at 97% confidence and Slosar et al. (2009) have measured the correlation function of the spin chirality and report, for the first time, of a signal at scales < 0.5 Mpc/h at the  $2 - 3\sigma$  level. This subject has received renewed interest not just for being a test of tidal torque theory but because the mechanism that produces angular momentum alignment is believed to create correlations between observed galaxy shapes, introducing a potential contamination to the cosmological weak lensing signal.

Observationally, the full information on the spin vector of a dark matter halo is very difficult to obtain. Concentrating on disk galaxies, the plane of the disk determines the axis of rotation of the disk of baryonic matter. For galaxies seen in projection, the observed galaxy ellipticity constrains the galaxy spin axis. For infinitely thin and perfectly circular disks, the spin vector axis would be known but not the spin "chirality" (the spin direction along the axis). For realistic disks, projection effects mean that what can be measured reliably is the projected spin axis. Information abut the spin chirality is absent in the study of galaxies ellipticity. Nevertheless, the chiral information is known for the sample of face-on galaxies of the Galaxy Zoo project <sup>1</sup>. Correlation of chirality therefore implies a correlation of the spin vectors.

An expectation of tidal torque theory is that haloes which formed together, and thus experienced a similar tidal field during their initial collapse, will have similarly aligned spin vectors. Galaxy chirality should thus be coherent on scales related to those of large scale structure.

Here we explore whether spatially coherent spin chirality (and therefore spin vectors) correlate with other galaxy properties that depend on the galaxy stellar population and star formation history. Our main finding is that the *absolute* value of the average spin direction of the galaxies located in a spatial patch (pixel), is correlated with past star formation activity in these galaxies, while we find no correlation with other galaxy properties like metallicity, or with the average spin itself, i.e. the universe does not have a preferred direction. The rest of the paper is organized as follows: §2 describes the galaxy sample selection and the methodology,

 $\S 3$  presents the results. In  $\S 4$  we present some discussion and draw our conclusions.

#### 2 SAMPLE SELECTION AND METHOD

In the Galaxy Zoo project, a sample of 893,212 galaxies were visually classified by about 90,000 users. The sample was selected to be sources that were targeted for SDSS spectroscopy, that is extended sources with Petrosian magnitude r < 17.77. Additionally, we included objects that were not originally targeted as such, but were observed to be galaxies once their spectrum was taken. Where spectroscopic redshifts were available, we found that galaxies have the mean redshift of z = 0.14 and the objects with the highest redshift reach  $z\sim 0.5.$  The galaxies thus probe our local universe at cosmological scales. Each object has been classified about 40 times from a simplified scheme of 6 possible classifications: an elliptical, a clockwise spiral galaxy, an anti-clockwise spiral galaxy, an edge-on spiral galaxy, a star / unknown object, a merger. Various cuts (hacking attempts, browser misconfigurations, etc.) removed about 5% of our data. The data were reduced into two final catalogues based on whether data was weighted or unweighted. In the unweighted data, each user's classification carried an equal weight, while in the weighted case, users weights were iteratively adjusted according to how well each user agreed with the classifications of other users. In both cases, the accrued classifications were further distilled into "super-clean", "clean" and "cleanish" catalogs of objects, for which we required 95%, 80% and 60% of users to agree on a given classification. In all cases, this is a statistically significant classification with respect to random voting; however, the human "systematical" error associated with it is difficult to judge. In any case, we are in the limit where taking more data will not change our sample beyond noise fluctuations as the votes are uncorrelated. A detailed account of the reduction procedures as well as the procedure to measure spin orientations, and removal of systematics is explained in Lintott et al. (2008) and Land et al. (2008).

We consider the sample of spiral galaxies of the Galaxy Zoo project for which the spin chirality (i.e. the direction of the galaxy arms winding) has been determined. This piece of information for each galaxy is what we refer to as halo spin chirality. In general, the gas of a galaxy should be rotating in the same direction as the halo: about 4% of the galaxies do not obey this (Pasha & Smirnov 1982), but there should be a strong –although not perfect–correlation between the angular momentum vector of gas and that of the dark matter halo hosting a galaxy (van den Bosch et al. 2002). Here we assume that the chirality of the galaxy is a proxy for the rotation direction of the host dark matter halo.

Our catalog of galaxy star formation properties is obtained from Panter et al. (2007). This catalog has been constructed from the spectroscopic main galaxy sample of the SDSSS-DR4 data release (Adelman-McCarthy et al. 2006). Star formation histories, metallicities, stellar masses and dust content, have been extracted using the MOPED (Heavens et al. 2000) algorithm, which allows for rapid extraction and parameter exploration of galaxy spectra using stellar population models. The method has been explored in detail in Panter et al. (2007) and has been tested

- Spin vector pointing ``up'' (s=1)
- x Spin vector pointing "down" (s=-1)

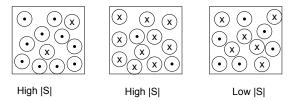


Figure 1. Graphical depiction for a given pixel size of what it means to have high value of  $s_j$ .

with the VESPA (Tojeiro et al. 2007) algorithm for accuracy and extent of degeneracies in the recovered parameters (see Panter et al. (2007); Tojeiro et al. (2007) for details). The star formation histories catalog from VESPA(Tojeiro et al. 2009) is available online<sup>2</sup>. While for the SDSS spectra, individual star formation histories are poorly constraint (Tojeiro et al. 2007) because of the low S/N, average properties sample are robust and well constrained; it is these average quantities that we use in our study. Panter et al. (2007) give a thorough and detailed explanation of the method, its shortcomings and advantages and we refer the interested reader to this paper for a detailed description of the star formation catalog used in the present work. The catalog contains about half million galaxies.

To create our final sample we match the above two catalogs, MOPED and Galaxy Zoo (keeping only galaxies that are classified as clean), to obtain a total of 12897 galaxies at redshift z < 0.2. The redshift distribution of our sample is fairly narrow (the redshift interval 0.012 < z < 0.13 encloses 90% of the galaxies, the maximum of the redshift distribution is  $z_m = 0.08$ . It is this sample that we use in our study. Note that the galaxies in the sample are spirals, and therefore the downsizing effect is not as extreme as in ellipticals.

We uniformly pixelize the survey using a range of pixel sizes. In what follows we use a flat concordance LCDM model to convert between redshifts and distances. In each pixel we define a pixel spin chirality  $S_j$  given by the average spin chirality for the galaxies in the pixel:  $S_j = \sum_{i=1}^{N_j} s_i/N_j$  where  $N_j$  denotes the number of galaxies in pixel j and  $s_i$  denotes a galaxy spin chirality;  $s_i$  can only take values of +1 or -1 while -1 <  $S_j$  < 1. For uncorrelated spin direction, within the errors  $S_j = 0$ , only for correlated spin direction the average spin chirality will be significantly non-zero (see Fig. 1). Note that when we compute the cross-correlation of galaxies quantities with the pixel spin chirality  $S_j$  we will use the absolute value,  $|S_j|$ . We will show that there is no

**Table 1.** Centre and boundaries ((l)ower, (c)enter, (u)pper) of the star formation bins in redshift (z) and look-back time  $t_{lb}$  in Gyr

bin	1 z	c z	u z	l $t_{ m lb}$	c $t_{\rm lb}$	u $t_{ m lb}$
11	0.0007	0.001	0.00145	0.00966	0.014	0.0200
10	0.00145	0.0021	0.003	0.0200	0.029	0.0414
9	0.003	0.006	0.0063	0.0414	0.06	0.0857
8	0.0063	0.012	0.013	0.0857	0.12	0.1776
7	0.013	0.0179	0.027	0.1776	0.26	0.3677
6	0.027	0.0419	0.057	0.3677	0.53	0.7614
5	0.057	0.0839	0.125	0.7614	1.10	1.5767
4	0.125	0.186	0.287	1.5767	2.27	3.2650
3	0.287	0.456	0.786	3.2650	4.70	6.7609
2	0.786	1.200	2.000	6.7609	8.46	10.32
1	2.000	4.000	8.000	10.32	12.09	13.00

correlation when we use the full value of  $S_j$  (including its sign).

Each galaxy in the sample (index i) has associated a stellar mass, a metallicity, a metallicity history and a star formation history. The star formation history is described by the star formation in independent bins (index  $\beta$ ),  $\psi_{\beta,i}$ : 9 equally spaced in look back time and two bins for high redshift star formation (see table 1). For each galaxy, the star formation is normalized to unity. For each pixel we also define a deviation from the mean star formation history given by the average star formation in each bin over the pixel galaxies minus the global average star formation:  $SF_{j,\beta} = \sum_{i=1}^{N_j} \psi_{\beta,i}/N_j - \langle \psi \rangle$ . Metallicity history is treated in the same way. Note that by comparing average quantities in each pixel rather than total quantities we are not directly sensitive to the galaxy local density. Correlation between chirality and density has been explored in Land et al. (2008).

We therefore have several pixelized maps: a map of spin chirality, and 24 maps of galaxy star formation properties (stellar mass, metallicity, 11 maps of star formation at different look back times, and similarly 11 maps for metallicity history).

To quantify a possible correlation between galaxy properties and spin coherence we use the Pearson correlation coefficient and explore how it varies as a function of pixel size, lag, and star formation properties. Errors are estimated by repeating the procedure with randomized spins. This cross-correlation in pixels of a finite size essentially contains information on integrated cross-correlation function below some pixel size. If certain properties correlate in two-point statistics up to a certain scale, our statistical test will pick it up.

## 3 RESULTS

We are interested in exploring if galaxies with a particular property have their spins aligned or randomly oriented with respect to their neighbours. In this respect we do not need to worry about projecting the spin vector on a common reference frame for all galaxies as was done by Land et al. (2008); Slosar et al. (2009) as we are only interested in the cross-correlation between the spatially averaged chirality of the galaxies and their star formation properties. We also in-

http://www-wfau.roe.ac.uk/vespa/

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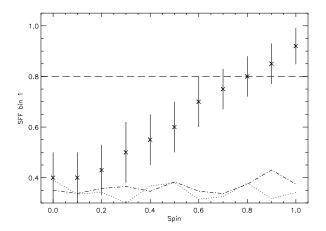


Figure 2. Relation between pixel-averaged star formation fraction in the oldest MOPED bin (1, see Table 1) and pixel-averaged absolute spin  $|S_i|$  (for a pixel size of 10Mpc/h) for all those galaxies that have formed more than 30% of their present stellar mass at z > 2.0. Due to the large number of pixels, instead of showing a scatter plot we sow the mean relation, error-bars show the standard deviation around the mean relation. Note that spiral galaxies that formed more than 30% of their stars at z > 2 have preferentially a coherent spin chirality. If we focus on those spiral galaxies that formed more than 80%, denoted by the dashed line, of their stars at z > 2 then virtually all of them have coherent spin chirality. The dotted and dash-dotted lines show the pixel-averaged star formation but for choices of the pixel size of 2Mpc/h and 50Mpc/h respectively. For these cases the value of the star-formation fraction as a function of absolute spin is consistent with zero as error bars are similar to the 10Mpc/h pixel-size case and are not plotted for clarity (see text for more details).

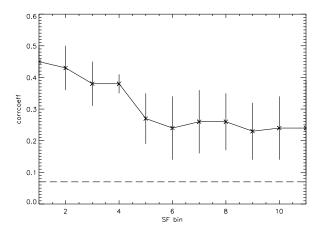
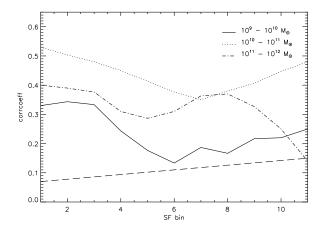


Figure 3. Pearson correlation coefficient between absolute value of pixel spin chirality and past star formation as a function of the start formation in look-back time bin number (see Table 1 for conversion between bin number and look-back time). The pixel size is  $10 \mathrm{Mpc}/h$ . The points are the mean of the correlation coefficient for several redshift slices. Error bars show jacknife estimates of the correlation coefficient rms by using several redshift slices, the dashed line shows the  $1-\sigma$  correlation level obtained with a randomized spin map. Galaxies with star formation in the oldest bin (1-3) show strong correlation with spin chirality (and therefore with spin alignment). The correlation decreases for galaxies with more recent star formation.



**Figure 4.** Same as Fig. 3 but for three different mass ranges. In this cases we use the projected map in order to increase the signal-to-noise. Note that the signal at bins 1-2 is dominated by galaxies in the mass range  $10^{10}-10^{11}$  M<sub> $\odot$ </sub>.

terpret the chirality of the galaxy spin as a proxy for the halo spin chirality.

Spins of the galaxies in our sample are spatially correlated (Slosar et al. 2009) and star formation properties are also spatially correlated with the large-scale cosmological structures (e.g., Sheth et al. (2006)). The cross correlation as defined in  $\S 2$  will indicate which galaxy property is mostly correlated with the large-scale tidal field responsible for spin alignment.

We find no correlation of the absolute value of the pixel spin chirality with stellar mass, metallicity or metallicity history but we find significant correlation with star formation history. Further, when we correlate the pixel spin chirality (not its absolute value but keeping the sign) with the star formation history we find no correlation or to be precise the Pearson coefficient we find is of order 4% at all look-back times, which is below the error in the coefficient itself (see below).

Fig.2 shows the relation between the pixel averaged star formation fraction  $(SF_{j,1})$  in the oldest MOPED bin (1, see Table 1) and the absolute value of the pixel-averaged spin  $|S_j|$  for all those galaxies that have formed more than 30% of their present stellar mass at z>2.0. Because of the large number of pixels a scatter plot is unclear; here the points indicate the mean relation and the error bars show the standard deviation around the relation. Note that spiral galaxies that formed more than 30% of their stars at z>2 have preferentially a coherent spin chirality. If we focus on those spiral galaxies that formed more than 80%, denoted by the dashed line, of their stars at z>2 then virtually all of them have coherent spin chirality. This implies that those galaxies that were in place at z>2 rotate on the same direction on scales of  $\sim 10 \mathrm{Mpc}$ .

To quantify our results we find that the Pearson correlation coefficient between absolute value of the pixel spin chirality and past star formation maps is maximum at zero-lag for a pixel physical size of  $\sim 10~{\rm Mpc}/h$ . For smaller pixel sizes ( $< 2{\rm Mpc}/h$ ) the number of galaxies per pixel decreases very rapidly. The correlation disappears for pixel sizes larger

**Table 2.** Per cent deviation in each look-back time star bin for the quantity  $|S_j|$  from zero, which means the universe has no preferred direction. Note that there is a negative bias at the % level but this error is below the error from the correlation analysis (see text).

SF bin	11	10	9	8	7 - 1
%	-0.7	-2.5	-3.4	-2.9	-3.8

than  $\sim 50$  Mpc/h. See also Fig. 1 where we show the value of the correlation for different pixel sizes.

We find that the correlation is greatest for galaxies which formed most of their stars in the past and decays for galaxies with most of their stars being formed recently.

Fig. 3 shows the Pearson correlation coefficient for the absolute value of the pixel spin chirality as a function of the star formation bin (see Table 1). The points have been obtained by computing the mean for several redshift slices of width  $\sim 100$  Mpc and the error bars shown are from the mean dispersion in the different,  $\sim$  10, redshift slices. The dashed line shows the error in the correlation coefficient obtained from randomly redistributing the values of the  $|S_i|$ map. We can see that for those galaxies with significant star formation in the oldest bins (1-4) the correlation with absolute value of pixel spin chirality is  $6\sigma$  above the noise level, while it decreases to slightly weaker levels for galaxies with significant star formation in their recent bins (8-11). This finding indicates that spiral galaxies with most of their star formation in the past have most of their galaxies rotating in the same direction with coherence length of 10 Mpc/h. To explore the correlation for separation smaller that 10  $\mathrm{Mpc}/h$  we have repeated the analysis with the projected catalog. The catalog depth implies that in the line of sight direction the cell size, R is always  $\sim 343 \text{ Mpc/}h$  thus diluting the signal if the signal coherence length is smaller than R. The higher density of objects however enables us to explore smaller separations. We find that the signal is maximal for cell sizes of 10 Mpc/h (given by the transversal cell size at  $z_m$ ) and decreases rapidly for cell sizes greater than 50  $\mathrm{Mpc}/h$ . As before, also in this case when considering the full value of the pixel spin chirality, i.e. keeping the sign, we obtain no statistically significant correlation.

These results indicate that the universe does not have a preferred direction and/or more importantly that human biases in classifying the rotation direction do not enter into our analysis.

Table 2 shows for the 11 look-back times, the percentage deviation from zero in the value of the pixel spin chirality when we consider the sign and demonstrates that a small bias at the 3-4% level remains, toward negative values of S but below the intrinsic error. To calculate the values of the bias in each look-back time bin we calculate  $\sum S_{\beta}$  for all the galaxies in that bin that contribute to more than 90% of the bin star formation. We have also verified that the strength of the correlation signal does not depend on how many galaxies are included in the sample by randomly sub-sampling the catalog, the error-bars of course increase when less galaxies are considered.

Because star formation is also correlated with mass (Sheth et al. 2006), we explore if the above correlation is driven by the mass of the galaxy. MOPED provides the

present and total stellar mass in the galaxy. In Fig. 4 we show the above correlation but for three mass ranges. The dashed line shows the correlation level for a map where the absolute values of pixel spins chirality have been redistributed randomly and therefore is a measure of the noise level. We note that the correlation at early times (bins 1-2) is dominated by galaxies in the mass range  $10^{10} - 10^{11} \text{ M}_{\odot}$ . (Recall that since the sample is approximately volume limited the number of galaxies in each for the mass bins decreases rapidly with increasing mass, so the trend is not driven by the number of galaxies in each mass bin). This is in contrast with the strong correlation found between mass and star formation in the past by Heavens et al. (2004); Panter et al. (2007). We conclude then that the observed correlation between spin chirality and early star formation is not driven by mass but by star formation activity.

So far we have used the galaxies from Galaxy Zoo classified as clean which limits our sample to only 12897 galaxies. Because there are many more galaxies in the MOPED catalog we have implemented the following algorithm to increase the Galaxy Zoo sample. We weight the chirality of a galaxy by the number of votes from the public. If most people voted for one direction this algorithm converges to the clean sample we used before. The results of the correlation so obtained are similar to Fig. 1 within the errors bars.

#### 4 DISCUSSION AND CONCLUSIONS

Halo spin directions correlate with the large-scale structure see e.g. Bailin & Steinmetz (2005); Hahn et al. (2007); Trujillo et al. (2006): halos in sheets tend to have their angular momentum parallel to the sheet, a weaker indication is observed for halos in filaments to have their spin perpendicular to the filament direction.

Spins directions are also correlated, as seen in observations (Slosar et al. 2009; Pen et al. 2000) and as predicted by tidal torque theory (Catelan & Porciani 2001; Catelan et al. 2001; Crittenden et al. 2001; Porciani et al. 2002).

We have found significant correlation between past star formation activity and the degree of coherence of spin chirality for galaxies in a spatial patch (pixel spin chirality). While we have only used the chiral information of nearly face-on galaxies, the detection of a non-zero signal can only be produced if spin orientations are correlated. The correlation is highest for regions in which galaxies have formed most of their stars in the past. We do not find significant correlations with spin coherence for any of the other measured galaxy properties that we have considered (metalicity, stellar mass, metalicity history).

We note that using chiral information rather than axis inferred from the projected ellipsoid is safer from the perspective of potential systematic effects. The reason for this is that inferred properties of stellar population are likely to be affected by the galaxy being viewed face-on or edge-on. These properties, on the other hand, cannot be affected by the galactic arms winding on way or another.

Our analysis indicates that neighboring spiral galaxies which have similar star formation histories also have their spins aligned. We can interpret this as the large-scale environement influencing dark matter halo spins, giving it a

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large scale coherence length, and that either halo spin, environment, or a combination of the two, influence galaxy star formation histories. This can be understood in the context of tidal-torque theory. Galaxies that have their spins aligned are formed in the same filament or sheet and at about the same time.

This correlation is stronger for regions comprising galaxies with older stars, while regions containing significant fractions of galaxies with recent star formation exhibit a smaller correlation with spin coherence. This can be understood as these galaxies being formed in the field and thus being affected by a random tidal field and at different epochs or having had a recent major merger, which would promote recent star formation but deviate the spin direction from that set by the cosmological tidal field.

Our results imply that in simulations of galaxy formation one should expect to detect the early formation of big spiral galaxies in the filaments around clusters. It is the halos in the filaments that should carry the majority of the star formation of the big spirals. Further, one would expect that most star formation today should be in the field, away from the filaments and that these objects should have randomly oriented spins. This finding indicate that spin and the correlation between spin and star formation are new, measurable quantities which offer a new complementary way to explore and quantify the effect of environment on star formation Bamford et al (2008). We are planning to explore these issues using cosmological simulations of galaxy formation.

Another possible implication for these results involve weak gravitational lensing studies. A weak lensing survey's potential to yield a faithful reconstruction of the cosmological distribution of dark matter is limited by the unknown intrinsic alignment of galaxy shapes. There is evidence that intrinsic galaxy shapes are spatially correlated Brown et al. (2002); Pen et al. (2000); Heavens et al. (2000), due to the fact that the alignment of galaxy disks orientations is induced by halo spins correlations Catelan et al. (2001).

Our results seems to indicate that, if the star formation history could be measured for at least some of the lensed galaxies, the properties of their star formation histories could be used to predict galaxies spin alignment and thus intrinsic shape alignment.

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